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Magnetic field amplification by relativistic shocks in a turbulent medium

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Abstract. We perform two-dimensional relativistic magnetohydrodynamic simulations of a mildly relativistic shock propagating through an inhomogeneous medium. We show that the postshock region becomes turbulent owing to preshock density inhomogeneities, and the magnetic field is strongly amplified due to the stretching and folding of field lines in the turbulent velocity field. The amplified magnetic field evolves into a filamentary structure in our two-dimensional simulations. The magnetic energy spectrum is flatter than Kolmogorov and indicates that a so-called small-scale dynamo is operating in the postshock region. We also find that the amount of magnetic-field amplification depends on the direction of the mean preshock magnetic field.

Keywords. turbulence, relativistic shock, MHD

1. Introduction

In the standard GRB afterglow model (e.g., Piran 2005; Mészáros 2006), the radiation is produced in a relativistic blastwave shell propagating into a weakly magnetized plasma. Detailed studies of GRB spectra and light curves have shown that the magnetic energy density in the emitting region is a small fraction $\epsilon_B \sim 10^{-3} - 10^{-2}$ of the internal energy density (e.g., Panaitescu & Kumar 2002). However simple compressional amplification of the weak pre-existing microgauss magnetic field of the circumburst medium can not achieve this magnetization (e.g., Gruzinov 2001). The leading hypothesis for field amplification in GRB afterglows is the relativistic Weibel instability which produces filamentary currents aligned with the shock normal. These currents are responsible for the creation of transverse magnetic fields (e.g, Medvedev & Loeb 1999). However, the size of the simulated regions is orders of magnitude smaller than the GRB emission region. It remains unclear whether magnetic fields generated on scales of tens of plasma skin depths will persist at sufficient strength in the entire emission region. On the other hand, in magnetohydrodynamic (MHD) processes, if the density of the preshock medium is strongly inhomogeneous, significant vorticity is produced in the shock transition. This vorticity stretches and deforms magnetic field lines and leads to amplification (e.g, Sironi & Goodman 2007). For the long duration GRBs, i.e., associated with iron core collapse of mass-losing very massive stars, density fluctuations in the interstellar medium may arise through several processes (e.g., Sironi & Goodman 2007).

Recently, Giacalone & Jokipii (2007) have performed non-relativistic MHD shock simulations that included density fluctuations with a Kolmogorov power spectrum in the preshock medium. They observed a strong magnetic-field amplification caused by turbulence in the postshock medium; the final rms magnetic-field strength is reportedly a hundred times larger than the preshock field strength. Here we investigate the magnetic-field amplification by turbulence in two-dimensional relativistic MHD simulations of a mildly relativistic shock wave propagating through an inhomogeneous medium.

2. Numerical Setup

In order to study the propagation of a mildly relativistic shock in an inhomogeneous medium, we use the 3D GRMHD code "RAISHIN" in two-dimensional Cartesian geometry ($x-y$ plane). A detailed description of the code and its verification can be found in Mizuno *et al.* (2006).

At the beginning of the simulations, an inhomogeneous plasma with mean rest-mass density $\rho_0 = 1.0$ and containing fluctuations $\delta\rho$ uniformly flows in the positive x-direction with speed $v_0 = 0.4c$ across the whole simulation region. The density fluctuations are generated so that they have a two-dimensional Kolmogorov-like power-law spectrum of the form $P_k \propto 1/[1+(kL)^{8/3}]$, where k is the wavenumber and L is the turbulence coherence length. The turbulence is obtained by summing over a large number of discrete wave modes. A detailed description of the method used to generate a fluctuation with a Kolmogorov-like turbulence spectrum can be found in Giacalone & Jokipii (2007). We choose the total number of modes to be $N_m = 50$, the maximum and minimum wavelength to be $\lambda_{max} = 0.5L$ and $\lambda_{min} = 0.025L$, and with a fluctuation variance of $\sqrt{<\delta\rho^2>} = 0.012\rho_0$.

We consider a low gas-pressure medium with constant $p = 0.01\rho_0 c^2$, where c is the speed of light. The equation of state is that of an ideal gas with $p = (\Gamma-1)\rho e$, where e is the specific internal energy density and the adiabatic index $\Gamma = 5/3$. The specific enthalpy is $h \equiv 1 + e/c^2 + p/\rho c^2$.

The preshock plasma carries a weak constant magnetic field ($B_0 = 4.5\times10^{-3}(4\pi\rho_0 c^2)^{-1/2}$). We investigate the effect of the magnetic field direction with respect to the shock propagation direction, by choosing fields parallel (B^x) or perpendicular (B^y) to the shock normal. The computational domain is $(x,y) = (2L, L)$ with $N/L = 256$ grid resolution. We impose periodic boundary conditions in the y-direction. In order to create a shock wave, a rigid reflecting boundary is placed at $x = x_{max}$. The fluid, which is moving initially in the positive x-direction, is stopped at this boundary, where the velocity v^x is set to zero. As the density builds up at $x = x_{max}$, a shock forms and propagates in the $-x$-direction. New fluid continuously flows in from the inner boundary ($x = 0$) and density fluctuations are advected with the flow speed. A detailed description of initial set-up for the simulation can be found in Mizuno *et al.* (2010).

3. Simulation Results

Figure 1a shows a 2D image of the total magnetic field strength at $t = 10.0L/c$ for the parallel field (B^x) shock case. When the preshock inhomogeneous plasma encounters the shock, the shock front is rippled, leading to significant, random transverse flow behind the shock. Since the preexsiting magnetic field is much weaker than the postshock turbulence, the turbulent velocity field can easily stretch and deform the magnetic field lines. This creates regions with larger magnetic field intensity. In the region near the shock front, the vorticity scale size is small but in the region far away from the shock front,

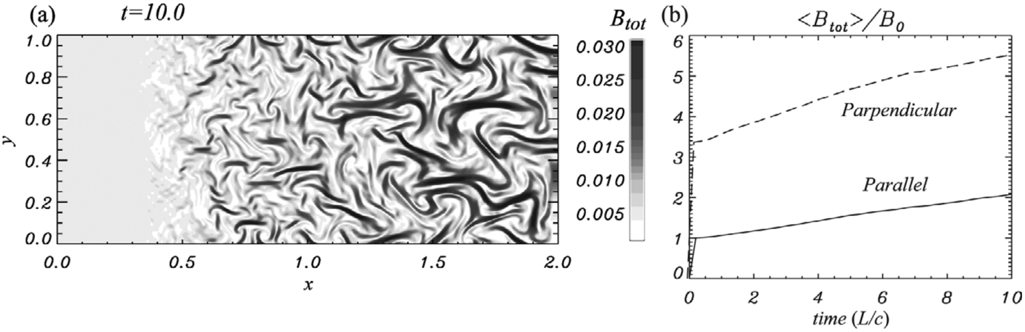

Figure 1. (*a*) Two-dimensional image of the total magnetic field strength at $t = 10.0L/c$ for the case of parallel field (B^x). (*b*) Time evolution of the volume-averaged total magnetic field strength in the postshock region normalized by the initial magnetic field strength.

the vorticity scale size becomes larger and the magnetic field is strongly amplified. The amplified magnetic field evolves in a filamentary structure. The average turbulent velocity in the postshock region is $\sim 0.02c$ at $t_s = 10$. The average sound speed and Alfvén velocity in the postshock region at $t_s = 10$ are $\sim 0.32c$ and $\sim 0.012c$. Thus the turbulent velocity is subsonic and super-Alfvénic in most of the postshock region.

Figure 1b shows the time evolution of the magnetic field indicated by the volume-averaged total magnetic field strength in the postshock region (whose size increases with time as the shock propagates away from the wall) normalized by the initial magnetic field strength. Note that the mean magnetic field strength is still increasing when the simulation was stopped. Thus, the mean magnetic field takes some time to saturate. The mean postshock magnetic field is stronger for the perpendicular field (B^y) (more than a factor 5 increase from the initial value) compared to the parallel field (B^x) (about a factor 2 increase from the initial value). This is because the magnetic field in the perpendicular field case is compressed initially by the shock. The magnetic field amplification from turbulent motion after magnetic field compression is almost same in both cases. The local maximum magnetic field strength is much larger than the mean magnetic field, about a factor of 13 and 26 times larger than initial magnetic field in the parallel and perpendicular cases respectively.

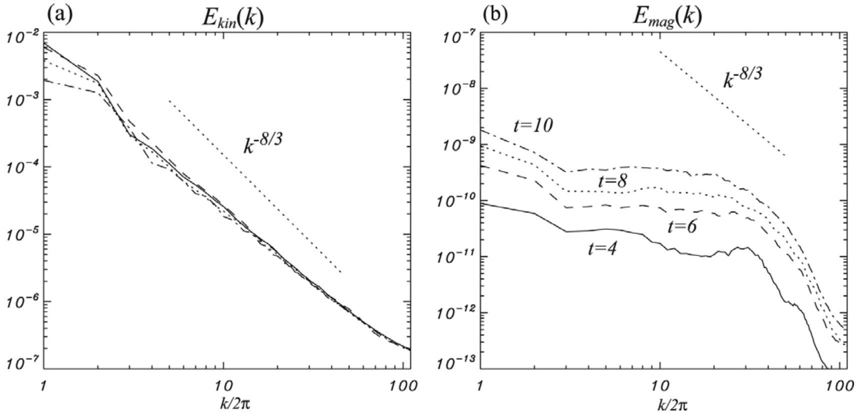

Figure 2. Spherically-integrated spectra of (*a*) the kinetic energy, (*b*) the electromagnetic energy. Different lines are for different times: $t_s = 4$ (*solid*), 6 (*dashed*), 8 (*dotted*), and 10 (*dash–dotted*). A dotted line indicates the power law $E(k) \propto k^{-8/3}$.

In order to understand the statistical properties of the turbulent fluctuations in the postshock region, it is helpful to observe their spectra.

Figure 2 shows spherically-integrated spectra of the kinetic and electromagnetic energy. The kinetic-energy spectra almost follow a Kolmogorov spectrum in all cases, $E_{kin}(k) \propto k^{-8/3}$, in two-dimensional systems. Initially the density in the preshock region is inhomogeneous with a Kolmogorov-like power spectrum, and this density power spectrum still exists in the postshock region. The kinetic-energy spectra do not change with time. The electromagnetic-energy increases over time, implying that the magnetic-field is not yet saturated. The magnetic energy power spectra are almost flat and strongly deviate from a Kolmogorov spectrum.

Spectra flatter than Kolmogorov are typical of the small-scale dynamo (e.g., Childress & Gilbert 1995; Balsara *et al.* 2004; Brandenburg & Subramanian 2005). In a small-scale dynamo, a forward cascade of magnetic energy from large scales to intermediate scales and an inverse cascade from small scales to intermediate scales are introduced. Therefore, the electromagnetic-field spectrum is flatter than Kolmogorov. A flat magnetic-energy spectrum is generally seen in turbulent-dynamo simulations (e.g., Balsara & Kim 2004).

The present simulation suggests a scenario whereby preexisting large-scale preshock density inhomogenities lead to strong magnetic field amplification in the postshock region. This process will be important in GRB and in AGN jet shocks.

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